Technical Support Report

A Brief Treatise on the Problems Associated with Using One Vehicle to Determine the Dynamometer Power Absorption for a Second Similar Vehicle

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Notice

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Abstract

The current EPA regulations for exhaust emission certification and fuel economy measurements allow a manufacturer the option of road testing a vehicle to determine a dynamometer adjustment which will subsequently be used for all vehicles of a similar class. In the process of using the road test results from one vehicle to determine the dynamometer adjustment for a second vehicle there is, of course, the potential for error. This report briefly discusses the magnitude of these possible errors.

Two specific cases are considered. In the first case the error is assumed to be random, unintentional and it is assumed that good engineering practices are used. In this instance it is estimated that the error associated with using a dynamometer adjustment obtained from test results of one vehicle to represent a second vehicle should be less than about one-half horsepower. This error is about 5 percent of the typical dynamometer adjustment, and is considered acceptable.

In the second case it is assumed that the potential for error is used in a systematic manner to result in a reduced loading for the second vehicle. In this instance when the possible errors are maximized to result in the optimum beneficial dynamometer loading of the second test vehicle, the possible errors are much greater. In this case it is concluded that a total error of 3.4 horsepower at 50 mi/hr is possible. The largest single contribution, 1.3 horsepower, is introduced by possible variations in the road versus dynamometer rolls behavior of the tire. The second largest possible contribution, 1.0 horsepower, may be introduced by brake drag effects.

Purpose

The purpose of this report is to discuss the technical problems associated with using one vehicle to determine the dynamometer adjustment to simulate the road experience of a second similar vehicle. Specifically, the magnitude of the errors which can occur in this instance are investigated. Two general cases are considered; the case where the errors are random and unintentional, and then secondly, the case where the potential for error is used in a systematic manner to result in a reduced loading for the second vehicle.

Background

The current EPA regulations for exhaust emission certification and fuel economy measurements allow a manufacturer the option of road testing a vehicle to determine a dynamometer adjustment which will subsequently be used for all vehicles of a similar class. In the process of using the road test results from one vehicle to determine the dynamometer adjustment for a second vehicle there is, of course, the potential for error. This report briefly discusses the magnitude of these possible errors.

Discussion

This section is divided into three subsections. The first section derives an expression for the possible error associated with using the dynamometer adjustment appropriate for one vehicle when testing a similar vehicle. The subsequent sections discuss the magnitudes of this error. In the first subsection the error is assumed to be random, unintentional and it is assumed that good engineering practices are used. In the second case it is assumed that the error is intentionally maximized to result in an optimum dynamometer load on the second test vehicle.

A. Development of an Expression for the Potential Error

When the vehicle is operated on road, the force on the vehicle is the sum of the aerodynamic drag, the tire rolling resistance and the drive train-chassis dissipative forces. This may be expressed as:

$$FR = Aero + 4(Tire) + Dtrain + NonDAxle \qquad (1)$$

where:

FR = the force experienced by the vehicle on the road

Aero = the aerodynamic drag of the vehicle

Tire = the tire rolling resistance force

Dtrain = the drive train dissipative forces

NonDAxle = the dissipative forces of the non-driving axle

The tire rolling resistance force is quite nearly proportional to the vertical vehicle load on the tire, at least in free rolling or nearly free rolling situations. For this reason it is frequently expressed as the product of a dimensionless rolling resistance coefficient times the vertical tire load. In this notation equation 1 becomes:

$$FR = Aero + 2[(Rr)(LDAxle)/2] + 2[(Rr)(LNDAxle)/2] + Dtrain + NonDAxle \quad (2)$$

$$= Aero + (Rr)(LDAxle) + (Rr)(LNDAxle) + Dtrain + NonDAxle$$

where

Rr = the tire rolling resistance coefficient on a road surface

LDAxle = the vertical load on the driving axle

LNDAxle = the vertical load on the non-driving axle

The sum of LDAxle and LNDAxle is, of course, the total vehicle weight. Therefore, equation 2 may be written as:

$$FR = Aero + (Rr)(W) + Dtrain + NonDAxle \quad (3)$$

where

W = the vehicle weight

On the dynamometer, the force acting on the vehicle is the sum of the dynamometer force and the drive train and drive tire losses. This may be expressed in the manner of equation 1 as:

$$FD = Dyno + 2[(Rd)(LDAxle)/2] + Dtrain \quad (4)$$
$$= Dyno + (Rd)(LDAxle) + Dtrain$$

FD = the total force acting on the vehicle when on the dynamometer

Rd = the tire rolling resistance coefficient for the tire on the dynamometer

Dyno = the total dynamometer force acting on the vehicle

If the dynamometer experience of the vehicle is to be equivalent to the road experience, FR of equation 2 must equal FD of equation 4 or:

$$Dyno + (Rd)(LDAxle) + Dtrain = Aero + (Rr)(LDAxle) + (Rr)(LNDAxle) + Dtrain + NonDAxle \quad (5)$$

Therefore the dynamometer force for exact dynamometer simulation of the vehicle road experience is:

$$\text{Dyno} = \text{Aero} + (\text{Rr})(\text{LDAxle}) - (\text{Rd})(\text{LDAxle}) + (\text{Rr})(\text{LNDAxle}) + \text{NonDAxle} \tag{6}$$

The rolling resistance on the dynamometer (Rd) is frequently expressed in terms of the ratio of tire-dynamometer rolling resistance to the tire-road rolling resistance. That is, in the form of the usual "one on the rolls equals two on the road". This may be written, without specifying the proportionality constant (x), as:

$$\text{Rd} = x\text{Rr} \tag{7}$$

Substituting equation 7 into equation 6:

$$\begin{aligned}\text{Dyno} &= \text{Aero} + (\text{Rr})(\text{LDAxle}) - (\text{Rr})(x)(\text{LDAxle}) \\ &\quad + (\text{Rr})(\text{LNDAxle}) + \text{NonDAxle} \\ &= \text{Aero} + \text{NonDAxle} + (\text{Rr})[(1-x)\text{LDAxle} + \text{LNDAxle}]\end{aligned} \tag{8}$$

Equations 2 and 3 describe the road experience of the vehicle while equation 4 describes the dynamometer experience. In addition, equations 8 describe the dynamometer force when the dynamometer is correctly adjusted to simulate the road experience. These equations can now be used to discuss the errors which can occur when the dynamometer adjustment appropriate for one vehicle is used to represent a different vehicle. This is, of course, the usual case when an alternate dynamometer adjustment is requested for a certification vehicle, based on road measurements of a prototype vehicle.

Equation 8 may be considered as the appropriate dynamometer adjustment, determined from the prototype vehicle. The appropriate dynamometer adjustment for the second, certification vehicle, may be expressed as

$$\text{Dyno}' = \text{Aero}' + \text{NonDAxle}' + (\text{Rr}')[(1-x')\text{LDAxle}' + \text{LNDAxle}'] \tag{9}$$

The error, if the dynamometer adjustment for the first vehicle is used when testing the second vehicle is the difference between equations 8 and 9. That is

$$\begin{aligned}\text{Error} &= \text{Dyno} - \text{Dyno}' \\ &= \text{Aero}-\text{Aero}' + \text{NonDAxle} - \text{NonDAxle}' + \\ &\quad (\text{Rr})[(1-x)\text{LDAxle} + \text{LNDAxle}] - (\text{Rr}')[(1-x')\text{LDAxle}' + \\ &\quad \text{LNDAxle}']\end{aligned} \tag{10}$$

The first two terms (Aero, NonDAxle) are simple vehicle-to-vehicle variations. The remaining terms represent a vehicle dynamometer interaction error, which is of course, influenced by the variations between the two vehicles. Labeling the last two terms as a vehicle-dynamometer interaction error:

$$\text{Error} = \text{Aero} - \text{Aero}' + \text{NonDAxle} - \text{NonDAxle}' + \text{VDIerror} \quad (11)$$

where

VDIerror = the vehicle dynamometer interaction error

$$= (\text{Rr})[(1-x)\text{LDAxle} + \text{LNDAxle}] - (\text{Rr}')[(1-x')\text{LDAxle}' + \text{LNDAxle}'] \quad (12)$$

It is desirable, from the EPA standpoint, to have the vehicle dynamometer interaction error, equation 12, be zero. The error can vanish in several ways. First, the two major terms can be equal in magnitude but opposite in sign. In general, the manner in which this would most likely occur would be if the tires of the two vehicles are functionally equivalent. That is:

$$\text{Rr} = \text{Rr}'$$

and

$$x = x' \quad (13)$$

In this case

$$\text{VDIerror} = (\text{Rr})[(1-x)(\text{LDAxle} - \text{LDAxle}') + (\text{LNDAxle} - \text{LNDAxle}')] \quad (14)$$

The error subsequently vanishes if the axle loads are equivalent.

The other possibility for zero error occurs when both major terms vanish independently. That is:

$$(1-x)\text{LDAxle} + \text{LNDAxle} = 0$$

and

$$(1-x')\text{LDAxle}' + \text{LNDAxle}' = 0 \quad (15)$$

This requires

$$\text{LDAxle} + \text{LNDAxle} = (x)\text{LDAxle}$$

and

$$\text{LDAxle}' + \text{LNDAxle}' = (x')\text{LDAxle}' \quad (16)$$

But the sum of the two axle loads is the vehicle weight, therefore the requirement is:

$$x = W/\text{LDAxle}$$
$$x' = W'/\text{LDAxle}' \quad (17)$$

This is the exact mathematical expression necessary for the dynamometer tire force dissipation assumption "one on the rolls equals two on the road" to be valid.

In the subsequent investigation of the dynamometer simulation error, it is convenient to express the prime quantities in terms of the change between the two vehicles. In this case:

$$\begin{aligned} Rr' &= Rr + \Delta Rr \\ x' &= x + \Delta x \\ LDAxle' &= LDAxle + \Delta LDAxle \\ LNDAxle' &= LNDAxle + \Delta LNDAxle \end{aligned} \tag{18}$$

In equation 18, ΔRr, Δx, ΔLDAxle and ΔLNDAxle represent the changes in these quantities between the two vehicles. These changes can, of course, be positive or negative. Inserting equation 18 into equation 12 gives the dynamometer interaction error as:

$$\begin{aligned} VDIerror = &- Rr[(1-x)\ \Delta LDAxle + \Delta LNDAxle \\ &-\Delta x(LDAxle + \Delta LDAxle)] \\ &-\Delta Rr\ [(1-x)LDAxle + LNDAxle \\ &+(1-x)\Delta LDAxle + \Delta LNDAxle \\ &-\Delta x(LDAxle + \Delta LDAxle)] \end{aligned} \tag{19}$$

The purpose of this report is to investigate the magnitude of the typical error, therefore neglecting terms which are products of the changes in the quantities is an acceptable approximation. This approximation is valid as long as the changes in the quantities are small compared to the original values. Using this approximation, the error can be expressed as:

$$\begin{aligned} VDIerror \approx &-Rr[(1-x)\ \Delta LDAxle + \Delta LNDAxle - \Delta xLDAxle] \\ &-\Delta R[(1-x)\ LDAxle + LNDAxle] \end{aligned} \tag{20}$$

Regrouping:

$$\begin{aligned} VDIerror \approx &-(Rr)(1-x)(\Delta LDAxle) \\ &-(Rr)(\Delta LNDAxle) \\ &+(Rr)(LDAxle)(\Delta x) \\ &-[(1-x)(LDAxle) + LNDAxle](\Delta Rr) \end{aligned} \tag{21}$$

The terms of equation 21 may be considered independently as:

$$\begin{aligned} LDAxle\ Error &= -(Rr)(1-x)(\Delta LDAxle) \\ LNDAxle\ Error &= -(Rr)(\Delta LNDAxle) \end{aligned} \tag{22}$$

Road-Rolls Error = (Rr)(LDAxle)(Δx)

Rolling Resistance Error = [(1-x)LDAxle + LNDAxle]ΔRr

The error, as expressed by equations 10 and 20 will be investigated in two approaches. In the first case, the magnitude of the probable errors when reasonable, "good engineering" practices are followed will be considered. In this case the errors result from minor vehicle or component variations. In the second case, the intent to propagate errors is assumed and the maximum possible errors will be considered.

B. The Magnitude of Probable Errors Expected with Reasonable "Good Engineering Practice"

If good engineering practice is used, the vehicle will be similar and, in general, the errors will be small.

Under the constraints of the applicability of coast down results to different vehicles, the first vehicle should represent the appropriate aerodynamics of the production vehicle. Therefore:

$$\text{Aero}' = \text{Aero} \qquad (23)$$

The wheel bearing, and brake drag of the vehicles should be similar, therefore:

$$\text{NonDAxle} \simeq \text{NonDAxle}' \qquad (24)$$

Assuming normal production tolerances a variation of $\pm$ 10 percent would seem reasonable for the brake drag. Recent EPA measurements have indicated the total non-driving wheel bearing and brake drag of a vehicle may be as much as one horsepower at 50 mph. A 10 percent variation would therefore be $\pm$ 0.1 horsepower at 50 mph.

In the case of the dynamometer simulation error, VDIerror, the previously discussed necessary condition for this error to vanish will be approximately met and the error is expected to be small. It would seem reasonable to expect a variation of 10 percent in nominally identical tires. Assuming this variation:

$$\Delta x = \pm\ 0.1\ x$$
$$\Delta Rr = \pm\ 0.1\ Rr \qquad (25)$$

The load on the non-driving axle might change by 100 pounds because of engine variation. Likewise the drive axle load might vary by 50 pounds because of minor body variations or the amount of fuel in the vehicle. Therefore, it is assumed:

$$\Delta \text{LDAxle} = \pm\ 100 \text{ pounds}$$
$$\Delta \text{LNDAxle} = \pm\ 50 \text{ pounds} \qquad (26)$$

Recent EPA investigations indicate appropriate values for the necessary tire parameters are:

$$x \simeq 1.7 \tag{27}$$

$$\begin{aligned} Rr &\simeq 10 \text{ pounds force/1000 pounds load} \\ &\simeq 10 \text{ lb/klb} \end{aligned}$$

In the case of a typical 4000 pound vehicle, it is reasonable to expect axle loads of approximately 2100 pounds and 1900 pounds for the non-drive axle and drive axles respectively. Therefore:

$$\begin{aligned} LDAxle &= 1900 \text{ pounds} \\ LNDAxle &= 2100 \text{ pounds} \end{aligned} \tag{28}$$

Substituting the values given in equations 25 through 28 into equation 22 gives the dynamometer simulation errors as:

LDAxle Error = 0.35 pounds

LNDAxle Error = -1.0 pounds

Road-Rolls Error = 3.23 pounds

Rolling Resistance Error = 0.77 pounds (29)

The worst case error occurs when all of the above error components have the same sign. In this case, the maximum error is 5.35 pounds force. The probable error is the RMS value of 3.48 pounds. At 50 mph these errors would be 0.71 and 0.46 horsepower respectively.

Including the possible brake drag error of 0.1 horsepower, the experimental error associated with minor vehicle variations should in all cases be less than 0.9 horsepower and would be expected to be less than about 0.5 horsepower.

In the calculation of the dynamometer simulation error, it should be noted that the third term dominated. This term originates from variations in the road versus rolls behavior of the tire. Therefore, the tire must be considered as an important aspect of the vehicle.

C. The Magnitude of Potential Intentional Errors

The previous section assumes reasonable good engineering judgment is used with the intent to keep errors small. This section examines the possibilities of errors deliberately propagated to achieve a low dynamometer adjustment. In this case it will be assumed that all errors are uniformly in the direction to optimize the dynamometer load on the second vehicle. In addition, maximum variations of the parameter are assumed. The first obvious possibility occurs if the first vehicle is more aerodynamic than the second. Constraints on vehicle type, frontal area and protuberance group reduce the possibility. However, by optimum selection of trim packages to minimize aerodynamic drag, it may still be possible to induce errors of 5 percent. In the case of a typical vehicle with an aerodynamic power requirement of about 10 horsepower at 50 mph this would be about 0.5 horsepower.

The second obvious place to introduce error is to eliminate the non-driving axle drag on the first vehicle. EPA measurements have indicated non-drive axle brake drag may dissipate as much as one horsepower. If this is typical, elimination of the drag would induce a one horsepower error.

Optimization of the vehicle dynamometer interaction error is a logical method to introduce additional errors. Errors can be introduced by optimizing the tire selection, the vehicle weight distribution, and the tire inflation pressure. The possible magnitude of each of these errors will be discussed independently.

1. Tire Selection

The obvious approach to achieve a low dynamometer adjustment is to optimize the vehicle tires on the first vehicle. By careful selection of tires within a generic tire type, it is probably possible to locate tires which have a rolling resistance 30 percent below the rolling resistance of the intended production tire. Equation 22 gives the error associated with the change in tire rolling resistance as:

$$\text{Tire Error} = [(1-x)\ (\text{LDAxle}) + \text{LNDAxle}](\Delta \text{Rr}) \qquad (30)$$

Using $\Delta R = 0.3R$, and the previously used parameters:

$$\begin{aligned}\text{Tire Error} &= 2.31 \text{ lbs}\\ &= 0.31 \text{ horsepower at 50 mi/hr}\end{aligned} \qquad (31)$$

It is likewise assumed that careful tire selection could result in tires which differed in the road to rolls characteristics by 30 percent. This effect could also be introduced or greatly increased by variations in tire operating pressures. The error introduced by this effect is:

$$\begin{aligned}\text{Road Rolls Error} &= (\text{Rr})\ (\text{LDAxle})\Delta x\\ &= 9.69 \text{ pounds}\\ &= 1.29 \text{ horsepower at 50 mi/hr}\end{aligned} \qquad (32)$$

2. Weight Distribution

Changes in weight distribution induce additional possible errors. If the vehicle weight distribution changed by 200 pounds, for example, one vehicle had an axle load which differed by 100 pounds from the design load and the second which also differed by 100 pounds in the opposite direction, the error would be:

$$\text{LDAxle Error} = Rr(1-x)(\Delta \text{LDAxle}) = 1.4 \text{ pounds} = .18 \text{ horsepower at 50 mi/hr} \quad (33)$$

Likewise:

$$\text{LNDAxle Error} = (Rr)(\Delta \text{LNDAxle}) = 2.0 \text{ pounds} = 0.26 \text{ horsepower at 50 mi/hr} \quad (34)$$

The maximum dynamometer simulation error is the sum of the absolute values of the individual errors. This sum is 15.4 pounds force or 2.0 horsepower at 50 mph. Including the maximum anticipated errors from aerodynamic effects, 0.5 horsepower and brake drag elimination, 1.0 horsepower, the total possible error is 3.4 horsepower at 50 mi/hr.

Conclusions

The error associated with using a dynamometer adjustment obtained from test results of one vehicle to represent a second vehicle is expected to be less than about one-half horsepower if "good engineering" practice and intent is used. This error is about 5 percent of the typical dynamometer adjustment, and is considered acceptable.

If the possible errors are consistently maximized to result in optimum beneficial dynamometer loading of the second test vehicle, the possible errors are much greater. In this case a total error of 3.4 horsepower at 50 mi/hr is possible. Of this total error, the largest single contribution, 1.3 horsepower, is from variations in the tire-rolls behavior of the tires. The second largest possible contribution, 1.0 horsepower, may be introduced by brake drag effects.